

## Measurements of Wave-Induced Fluctuations in Underwater Radiance Under Various Surface Boundary Conditions

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### LONG-TERM GOALS

This project is part of the Radiance in a Dynamic Ocean (RaDyO) program which aims at developing an understanding of variability in underwater radiance distribution and its relation to dynamic processes within the ocean-atmosphere boundary layer.

### OBJECTIVES

The principal objective of our project is to measure wave-induced fluctuations in underwater light field under various sea-surface boundary conditions. The specific objectives include the characterization of wave-induced fluctuations in downwelling irradiance and radiance as a function of various environmental parameters such as wind/wave conditions, sky radiance distribution, direction of radiance observation, depth of observation, and water optical properties. The central theme of our study is to characterize light fluctuations at shallow depths caused by surface wave focusing under clear skies. The focusing events are the most intense fluctuations that occur on temporal scales as short as milliseconds. The most prominent manifestation of this phenomenon is high-amplitude short-duration pulses of focused light, which we refer to as light flashes (Dera and Stramski, 1986; Stramski, 1986).

The primary objectives for this reporting period were: (i) analysis of data collected during the RaDyO experiments in the Santa Barbara Channel (September 2008) and off Hawaii (August-September 2009), (ii) analysis of data collected during our special additional experiment carried out in the Adriatic Sea off Venice from the Aqua Alta Research Platform (June 2009), and (ii) preparation of publications and conference presentations.

### APPROACH

The basic component of our approach involves in situ measurements of high-frequency fluctuations in underwater light field produced by surface waves under various boundary conditions. As reported previously, we developed the Underwater Porcupine Radiometer System, which includes twenty three

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light sensors providing a capability to measure downwelling irradiance and downwelling radiance with a high sampling frequency of 1 kHz. Sixteen sensors measure radiance at a single waveband (532 nm) at different zenith angles within two orthogonal azimuthal planes. Seven sensors measure downwelling plane irradiance at different wavelengths (365, 410, 443, 488, 532, 610, and 670 nm). In addition, the underwater unit is equipped with a depth sensor, temperature sensor, compass, and a rotator that allows us to control the spatial orientation of radiance sensors with respect to azimuthal direction.

Our approach to conduct field experiments involves the acquisition of time-series data (typically 10-min time-series) of light fluctuations at various depths with a 1 kHz sampling rate. The typical 10-min time-series includes 600,000 data points for each sensor. These data are acquired at depths ranging typically from about 0.5 m to 10 m. Most measurements are taken at shallow depths within the top 5 m of the ocean where wave-induced light fluctuations are most intense. The actual strategy for acquiring the data in the field is adjusted during experiments depending on variations in environmental conditions (wind, waves, sky conditions, etc.). This strategy may, for example, consist of the acquisition of successive time-series over a prolonged period of time (hours) at a single depth (e.g., 1 m) or a change of the measurement depth after every 10-min time series. With regard to data analysis, our approach involves the use of various statistical methods for the analysis of stochastic time-series data. The traditional analysis of random processes provides several statistical characteristics of light fluctuations such as statistical moments, probability density function, and frequency spectral density function. Special methods, referred to as the threshold analysis, are used to provide the statistics describing the frequency and duration of wave-focused pulses of focused light, i.e., light flashes.

This project is conducted in collaboration with the Institute of Oceanology, Polish Academy of Sciences (IOPAS) and the new instrumentation was developed at IOPAS. The key participants in the project from IOPAS are Dr. Miroslaw Darecki and an electro-optical engineer Mr. Maciej Sokolski.

## WORK COMPLETED

During the first RaDyO experiment in the Santa Barbara Channel in 2008, we collected nearly 230 time-series of light fluctuations from FLIP. During the Hawaii experiment in 2009 we collected about 200 time series of light fluctuations. During a 7-day experiment from the Aqua Alta Research Platform in the Adriatic Sea off Venice we acquired over 100 time-series with the Porcupine instrument. The main objective of this experiment was to test the influence of the collector size on the measured fluctuations in downwelling plane irradiance.

Data processing and most computations for determining the statistics of light flashes caused by wave focusing are completed. The portion of this data set was used in collaboration with Dr. George Kattawar's group to compare our measurements of wave focusing with their model that couples radiative transfer and surface waves. This collaboration resulted in a paper published in Applied Optics (You et al., 2010). Other analyses of light flashes are underway. Some results from the analysis of light flashes were presented at the 2010 Ocean Sciences Meeting in Portland (Stramski and Darecki, 2010) and preparation of a manuscript for publication is in progress.

During the reporting period, our analysis of Porcupine data was also focused on the probabilistic structure of the underwater light field under a wind-disturbed sea surface, which is presently poorly characterized. We examined the vertical changes in the probability distribution of downwelling

irradiance,  $P(E_d)$ , within the ocean surface layer (from about 0.5 m to 10 m) under clear sky conditions using datasets from the Santa Barbara Channel, Hawaii, and Venice (Aqua Alta Research Platform) experiments. In this analysis we defined the following variables:  $x = E_d/\langle E_d \rangle$  is the normalized irradiance;  $y = [x - \text{mean}(x)]/\text{sd}(x)$  is the standardized irradiance;  $X$  and  $Y$  are log-transformed normalized and standardized irradiances, and  $P()$ ,  $F()$ , and  $Q()$  are the probability distribution, cumulative probability distribution, and quantile function, respectively. The variables  $x$ ,  $y$ ,  $X$ ,  $Y$  are used as arguments of the  $P()$ ,  $F()$ , and  $Q()$  functions. The skewness  $\gamma_1$  (asymmetry factor) and kurtosis  $\gamma_2$  (peakedness factor) of the probability distributions were calculated. The departure of the experimental probability functions from the theoretical normal (or log-normal) distribution was examined using the RMSD (the root mean square difference) and  $r^2$  (squared correlation coefficient) of the quantile-quantile (Q-Q) plot between the quantiles of standardized data of experimental and normal (or log-normal) distributions. The RMSD and  $r^2$  were calculated within the quantile region from 0.1% to 99.9%. Overall 150 time-series measurements were used in this analysis, which were selected from a total of about 450 measurements made during the three field experiments. This dataset corresponds to clear sky conditions with unobstructed sun disk, a range of wind speed from about 2 to 12 m/s, and a range of solar zenith angle from  $10^\circ$  to  $75^\circ$ . At the present phase of data analysis, we focus on irradiance measurements taken at a light wavelength of 532 nm.

## RESULTS

Our results show that the probability distribution of instantaneous downwelling irradiance  $E_d$  at shallow depths between the surface and a few meters is highly skewed towards large instantaneous values of  $E_d$ . This result is associated with wave focusing of sunlight and indicates that the light fluctuations due to wave focusing at near-surface depths depart significantly from the normal (Gaussian) process. Example comparison of probability distribution of standardized downwelling irradiance,  $P(y)$ , obtained from time-series measurements at a depth of about 1 m during the Santa Barbara Channel experiment with the theoretical curve of normal distribution is shown in Fig. 1. This figure also shows results for the cumulative probability distribution and for quantile-quantile (Q-Q) plot of the experimental standardized irradiance versus theoretical standardized variable that satisfies the normal distribution. The departure between the experimental distribution and theoretical normal distribution is illustrated as a difference between the highly non-linear Q-Q plot (black line in the right panel of Fig. 1) and the 1:1 straight line representing the perfect agreement between the distributions (red line).

Within the top 10 m of the ocean, large vertical changes occur in the probability distribution of downwelling irradiance, the associated skewness and kurtosis coefficients, and the parameters RMSD and  $r^2$  calculated from the Q-Q plot with the normal distribution used as a theoretical reference (Fig. 2). At shallow depths immediately below the ocean surface, i.e., between about 0.3 m and 1 m,  $P(y)$  is highly skewed with positive asymmetry ( $\gamma_1 > 1$ ) and leptokurtic ( $\gamma_{2-3} > 2$ ). The values of  $\gamma_1$  and  $\gamma_{2-3}$  depart significantly from the value of zero that corresponds to the normal distribution. The RMSD values calculated from the Q-Q plots are greater than 20% at these near-surface depths, which further support significant departure from normality. With increasing depth towards 10 m, the probability distribution of irradiance appears to approach the Gaussian distribution. This is indicated by both the skewness and kurtosis coefficients approaching the values of the normal distribution. Also, the RMSD values decrease (and the  $r^2$  values increase) with increasing depth, which indicates that the Q-Q plots are closer to the 1:1 line representing the agreement between the experimental and normal distributions. For example, at depths below 5 m the RMSD values are less than 10%. However, the

extremities of the experimental distribution (i.e., within the regions of standardized irradiance outside the 0.1 to 99.9% quantiles) are not consistent with the normal distribution, even at a depth of 10 m. At the lowest extremity (i.e., for the lowest values of standardized irradiance), the experimental  $P(y)$  is typically smaller than the theoretical normal law predicts. The presence of diffuse background in the downwelling irradiance field likely explains this result. In contrast, at the highest extremity (i.e., for the highest values of standardized irradiance), the experimental  $P(y)$  is typically higher than the normal law predicts. This observation is caused by the presence of the extremely intense flashes in downwelling irradiance due to wave focusing of sunlight.

Although the results in Fig. 2 show rapid vertical transformation of irradiance fluctuations from non-normal towards normal process within the uppermost oceanic layer of ~10 m thickness, the normal distribution does not provide adequate description of the probabilistic structure of downwelling light field at these near-surface depths. It is of interest to analyze similar results for the log-transformed irradiance to see potential agreement or departure between the experimental probability distributions and the log-normal distribution. Figure 3 shows that whereas the log-normal distribution provides closer, or in many cases good approximation of the experimental distributions, it still cannot be used as a universal model. The RMSD values are generally from a few percent to 10% throughout the near-surface layer. Similarly to a normal fit, the extremities of the experimental  $P(Y)$  are often poorly modeled with a log-normal law. In contrast to a normal fit, however, the quality of the log-normal fit does not show strong dependence on depth. This is seen the vertical patterns of all presented parameters, skewness, kurtosis, RMSD, and  $r^2$ .

Various environmental parameters influence the probability distribution of downwelling irradiance in the surface ocean. One of the most interesting aspects of our research is the analysis of the relationships between the statistics of irradiance fluctuations and wind-wave parameters. The influence of wind speed (which is here used as a proxy for surface waves) on the parameters characterizing the probabilistic structure of irradiance is shown in Fig. 4 for a depth of ~1 m under conditions of sunny skies and relatively high solar elevation. The main effect of increasing wind speed is to reduce the skewness of the probability distribution which is accompanied by a decrease in the RMSD and an increase in  $r^2$ . These changes indicate that the increase in wind speed has a qualitatively similar effect on the probability distribution as an increase in the depth of observation, i.e., the distribution tends to change towards the normal distribution, albeit the normality is not reached. The explanation for the observed effect of wind is that under stronger winds the sea surface is efficiently diffusing the incident direct solar radiation, and as a result the focusing effects underwater are greatly reduced.

Our results from the threshold analysis of irradiance time-series point to a wealth of novel information about the statistics of light flashes caused by surface wave focusing. For example, we observed that the maximum amplitude of light flashes can exceed the time-average irradiance at near-surface depths by a factor greater than 10. Such high intensity flashes in underwater light field have never been reported in the past. These pulses represent the highest transient concentrations of solar energy that occur in natural environments, which likely have important implications to photochemical reactions within the near-surface layer of the ocean. Figure 5 shows example calculations of radiant energy associated with these strongest flashes measured in the Santa Barbara Channel at a depth of about 1 m under environmental conditions of clear skies and moderate winds, which favor wave focusing. Under these conditions the time-average irradiance integrated within the visible spectral region between 400 and 700 nm was about  $300 \text{ W m}^{-2}$ . This corresponds to quantum irradiance or photosynthetically

available radiation (PAR) of more than  $1300 \mu\text{E m}^{-2} \text{s}^{-1}$  (where  $\mu\text{E}$  is equivalent to  $\mu\text{mole quanta}$ ). Our estimate of irradiance associated with the strongest flash recorded during these measurements is about  $2800 \text{ W m}^{-2}$  or  $12800 \mu\text{E m}^{-2} \text{s}^{-1}$ , which is nearly 10 times higher than the average irradiance. We note that these values, albeit integrated only over the visible spectral range, are more than two-fold higher than the solar constant that covers the entire range of electromagnetic wavelengths produced by solar radiation.

## **IMPACT/APPLICATIONS**

The major impact of this project is to provide novel data and understanding of wave-induced fluctuations in underwater light field. This phenomenon has been scantily investigated in the past. Our measurements and analyses are expected to provide critical information for achieving science objectives of the RaDyO program, including the development and validation of time-dependent coupled surface wave-radiative transfer model. Our findings are also expected to have broader implications beyond the disciplines of ocean optics and physics, specifically in the areas of ocean biology and photochemistry.

## **RELATED PROJECTS**

This effort is related to other projects funded through the RaDyO program.

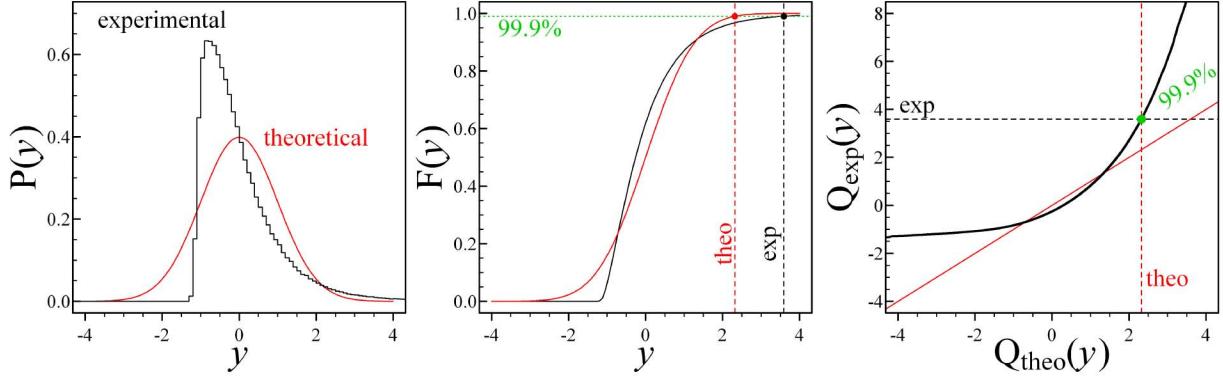
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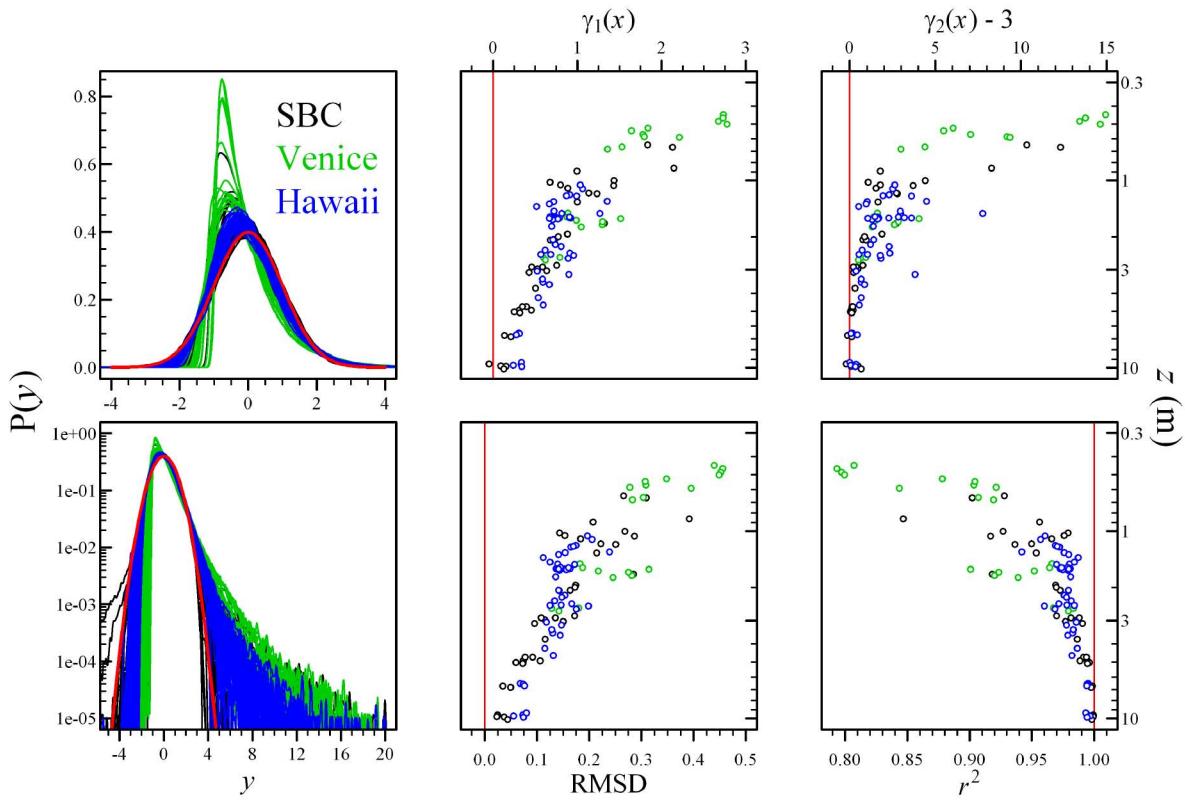
You, Y., D. Stramski, M. Darecki, and G. W. Kattawar. 2010. Modeling of wave-induced irradiance fluctuations at near-surface depths in the ocean: a comparison with measurements. *Applied Optics*, 49, 1041-1053.

## **PUBLICATIONS**

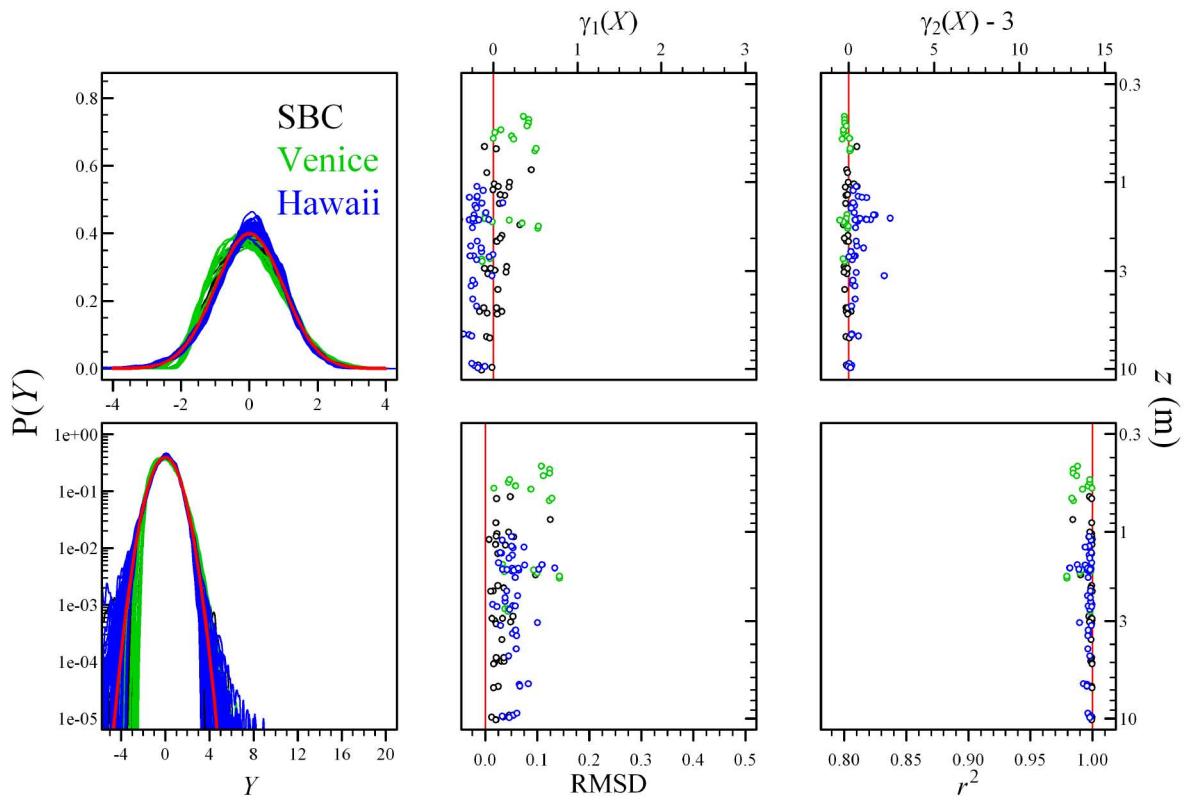
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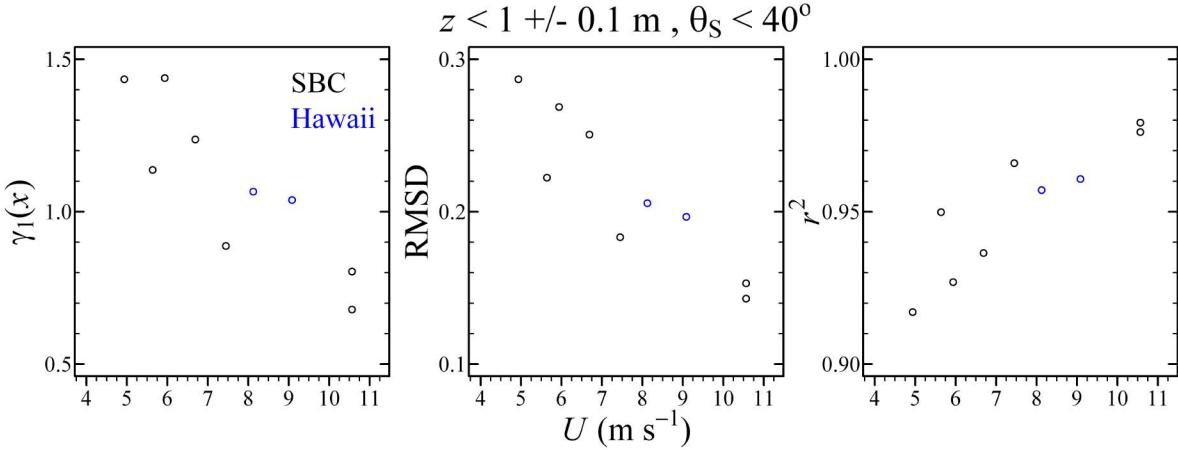
**Figure 1.** Left panel: Example comparison of probability distribution of standardized downwelling irradiance obtained from time-series measurements at a depth of about 1 m during the Santa Barbara Channel experiment (black line) with the theoretical curve of normal distribution (red line). Middle panel: same as the left panel but for the cumulative probability distribution. Right panel: The quantile-quantile (Q-Q) plot for the experimental standardized irradiance versus theoretical standardized variable satisfying the normal distribution (black line). The red line shows the Q-Q plot corresponding to the perfect agreement (i.e., 1:1 line) between the experimental and theoretical (normal) probability distributions. The departure between the experimental and theoretical distributions is highlighted for the quantile of 99.9%.



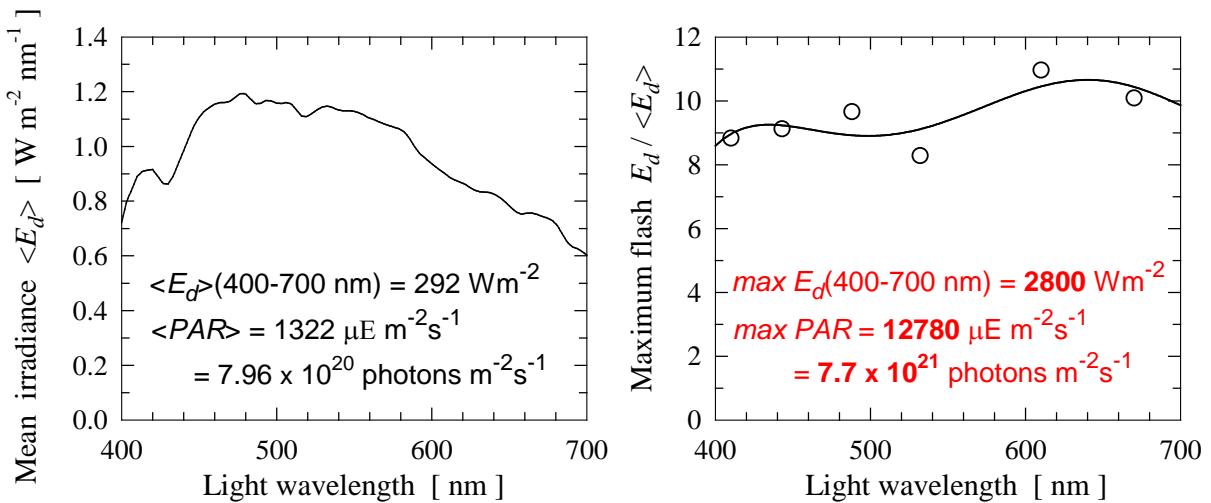
**Figure 2. Left panels:** Probability distributions  $P(y)$  of standardized downwelling irradiance with the probability plotted in linear scale (top left panel) and logarithmic scale (bottom left panel). **Middle and right panels:** Vertical changes in skewness  $\gamma_1$ , kurtosis  $\gamma_2 - 3$ , and the parameters calculated from the Q-Q plot, RMSD and  $r^2$ . Results from the Santa Barbara Channel, Hawaii, and Venice experiments are plotted in black, green, and blue, respectively. Data with sun zenith angle smaller than  $40^\circ$  were selected for this presentation. The range of wind speed for the presented data is 2 - 11.5 m/s.



**Figure 3.** Same as Figure 2 but for the log-transformed standardized downwelling irradiance.



**Figure 4.** Skewness of the probability distribution of irradiance, root mean square difference (RMSD) and squared correlation coefficient ( $r^2$ ) calculated from the Q-Q plot with the normal distribution as a theoretical reference, plotted as a function of wind speed for the Santa Barbara Channel (in black) and Hawaii (in blue) data acquired at a depth of 1 m ( $\pm 0.1$  m) under sunny skies with the solar zenith angle smaller than  $40^\circ$ .



**Figure 5.** Left panel: Spectral distribution of time-averaged downwelling irradiance measured during the Santa Barbara Channel experiment at a depth of about 1 m under sunny conditions. The values of integrated irradiance for the visible spectral region 400-700 nm are shown in terms of energy and number of photons per unit time and unit area. Right panel: Same as left panel but instead of time-average irradiance, the results are shown for the magnitude of irradiance associated with the strongest flash. As shown, the amplitude of the strongest flash exceeded the time-averaged irradiance by a factor ranging from about 8 to 11 at different light wavelengths.